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NOAA Technical Memorandum NMFS-PIFSC-12

October 2007

2006 Sea Turtle and Pelagic Fish Sensory Physiology Workshop, September 12-13, 2006

Compiled and Edited by

Yonat Swimmer
and
John H. Wang

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For further information direct inquiries to

Chief, Scientific Information Services
Pacific Islands Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce
2570 Dole Street
Honolulu, Hawaii 96822-2396

Phone: 808-983-5386
Fax: 808-983-2902

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2006 Sea Turtle and Pelagic Fish Sensory Physiology Workshop, September 12-13, 2006

Compiled and Edited by

Yonat Swimmer[1] and John H. Wang[2]

[1]Pacific Islands Fisheries Science Center
National Marine Fisheries Service
2570 Dole Street
Honolulu, Hawaii 96822-2396

[2]Joint Institute for Marine and Atmospheric Research
University of Hawaii
Honolulu, Hawaii

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SUMMARY

The five species of sea turtles found in the Pacific Ocean are either listed under the U.S. Endangered Species Act of 1973 as threatened (loggerhead, *Caretta caretta*; green, *Chelonia mydas*; and olive ridley, *Lepidochelys olivacea*) or as endangered (leatherback, *Dermochelys coriacea* and hawksbill, *Eretmochelys imbricata*). Many Pacific nesting populations of these turtles have seen a recent decline. These declines may be based on multiple factors, including direct mortality as a result of harvesting of adults and juveniles, poaching of eggs on nesting beaches, natural mortality by disease and predation, destruction and degradation of suitable habitat for nesting beaches, as well as the incidental capture of sea turtles in fishing gear.

There is a growing concern that interactions with fisheries, specifically longline fishing operations, negatively affect sea turtle populations worldwide. The level of sea turtle bycatch in pelagic longline fisheries is of great concern to environmentalists, the fishing industry, and fisheries managers alike. In the United States, recent protective measures have resulted in legally mandated gear modifications (e.g., large circle hooks) as well as time-and-area fisheries closures in both the Pacific and Atlantic Oceans. However, for a number of reasons, such measure may not be practical in all fisheries, and thus other methods of reducing sea turtle bycatch should also be considered.

Factors that attract sea turtles and target fish species to longline gear and bait are not well understood, but numerous sensory cues may be involved. In 2001, NOAA Fisheries scientists created the Sensory Biology Working Group and launched a multidisciplinary, interagency research program to investigate the visual, auditory, and chemosensory abilities of sea turtles and pelagic fishes. The purpose of the research was to identify differences between turtles and pelagic fish species that may be used to develop gear and bait attractive to fish but unattractive to sea turtles or undetectable by them. The primary objective of the research is to develop techniques and/or commercially viable devices that eliminate or substantially reduce interactions of sea turtles with longline fishing gear while not reducing catch rates of the targeted fish species to unacceptable levels.

Research projects have been underway since 2001, supported by funding from the Pacific Islands Fisheries Science Center (PIFSC), NOAA Fisheries, in Honolulu, Hawaii. Because of the complexity of the research, projects have necessarily involved a large and diverse team of scientists. Collaborating scientists have held three meetings prior to the 2006 meeting to discuss research progress. A Technical Memorandum[1], published as a result of this work, is available on the NOAA/PIFSC web site: http://www.pifsc.noaa.gov/tech/NOAA_Tech_Memo_PIFSC_7.pdf.

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[1] Swimmer, Y., and R. Brill (eds.) 2006. Sea Turtle and Pelagic Fish Sensory Biology: Developing Techniques to Reduce Sea Turtle Bycatch in Longline Fisheries. U.S. Dep. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-PIFSC-7, 106 p.

This report summarizes findings reported by collaborating scientists at the 4th Sea Turtle and Pelagic Fish Sensory Physiology Workshop hosted by the Virginia Institute of Marine Sciences Eastern Shore Laboratory in Wachapregue, Virginia during September 12-13, 2006. Participants of this workshop included NOAA fisheries biologists, researchers from U.S. and foreign universities, and consultants from private companies. A list of participants and their affiliations is included at the end of this report.

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VISION IN SEA TURTLES AND BLUE WATER FISHES

Kerstin A. Fritsches
VTHRC, Queensland Brain Institute, School of Biomedical Sciences
University of Queensland, Australia
Kerstin.Fritsches@uq.edu.au

Fritsches examined the visual capabilities of sea turtles and a number of blue water fishes in an effort to identify differences that could be used to design more species-specific fishing gear, specifically aimed to attract fish and remain unattractive to sea turtles. Identifying potential differences between sea turtles and pelagic fishes in their ability to detect colors was one avenue she explored. While determining the potential spectral (color) sensitivity of the fishes' photoreceptors, Fritsches found that billfishes (*Xiphias gladius, Makaira sp.)* and bigeye tuna (*Thunnus obesus*) have a narrower sensitivity range, often limiting their vision to "blue/green" wavelengths of light, whereas green turtles can see longer wavelengths of light, indicating their ability to see well into the "red" (Fig. 1).

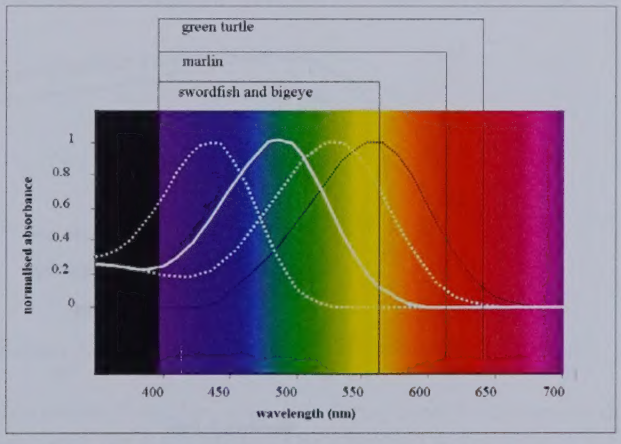


Figure 1.--Hypothesized spectral sensitivities of marine fishes and turtles.

In loggerhead turtles (*Caretta caretta)*, detailed anatomical examination of the eye showed that several different colored oil droplets (orange, yellow, and clear/colorless) were located over photoreceptors. These droplets act as color filters and the pairing of cones (photoreceptors) and oil droplets are likely to create superior color discrimination abilities in sea turtles compared to the blue water fish which all lack oil droplets (Fig. 2).

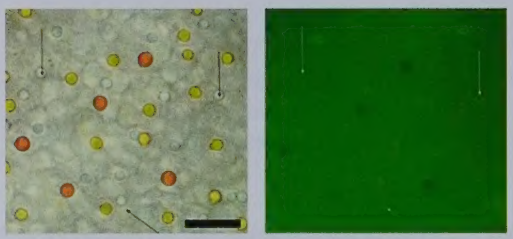


Figure 2.--Oil droplets act as color filters within the photoreceptors.

Fritsches determined that the lenses of mahimahi (*Coryphaena hippurus*) and several species of billfishes block ultraviolet (UV) light, while the ocular media (cornea, lens, and vitreous humor) of green turtles transmit this waveband to the retina, potentially allowing these animals to perceive UV light. Anatomical and optical results indicate that sea turtles can see in the UV waveband, while blue water fishes cannot, thereby suggesting UV light as a possible selective "communication channel" in sea turtles (Fig. 3).

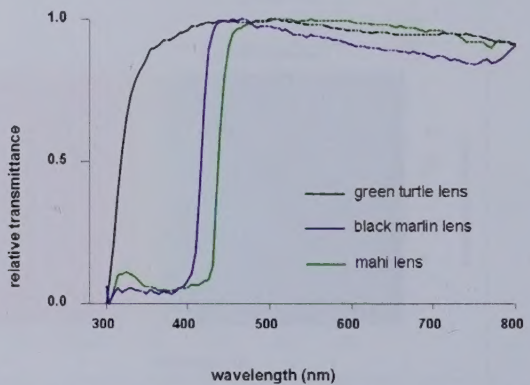


Figure 3.--Selective "Communication channel" (between 300 and 400 nm) allowing green turtles to perceive UV light, yet not visible to mahimahi or black marlin.

Fritsches also conducted behavioral experiments with hatchling loggerheads examining the color preference and visual capabilities of loggerheads using both orientation tanks (swimming) and Y-mazes (crawling). Fritsches found that all colors (with equal light intensity) attracted turtles with the exception of red light. Interestingly, loggerhead turtles tested did not exhibit the xanthophobia found in Florida loggerheads, whereby hatchlings avoided yellow light (Witherington and Bjorndal, 1991; Fig. 4). Fritsches speculated on differences between Australian vs. Florida loggerheads in their responses to light.

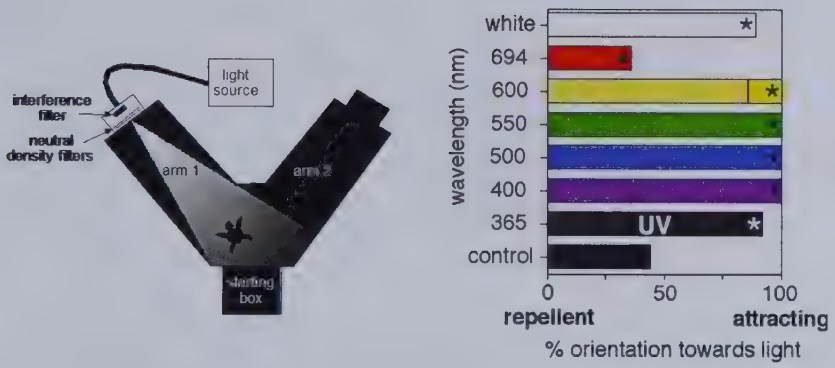


Figure 4.--Y-maze orientation studies to determine turtles' responses to lights of varying wavelengths (colors).

These crawling (and swimming) experiments also suggest that turtles can perceive wavelengths in the UV range. In Figure 5, the red dots show the orientation of the turtle recorded (every 20 sec over 10 min) with the UV Light Emitting Diode on, while the green dots show the positions of the same animal with the UV light turned off.

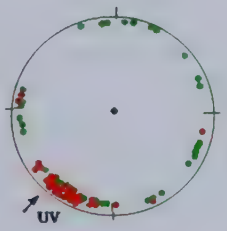


Figure 5.--Turtles' behavioral responses to UV light.

Using the Y-maze assay, Fritsches also developed a methodology to determine how bright a light has to be in order for a sea turtle to be attracted to (or simply see) it. Further experiments that test different wavelengths will reveal wavelengths perceivable by sea turtles. Fritsches also tested how the rate of flickering (flashing) influences turtles' perception of that light. In her experiments, she presented duty cycles of 50% on/50% off. Fritsches found that turtles did not discriminate between flashing and steady light, as long as both lights were presented at the same light intensity (Fig. 6). Fritsches commented on the potential of presenting a color that is less visible to sea turtles using flashes with long off phases as stimuli that would be less visible to sea turtles. However such stimuli would have to be tested for their attractiveness to blue water fishes, depending on the use of the stimuli.

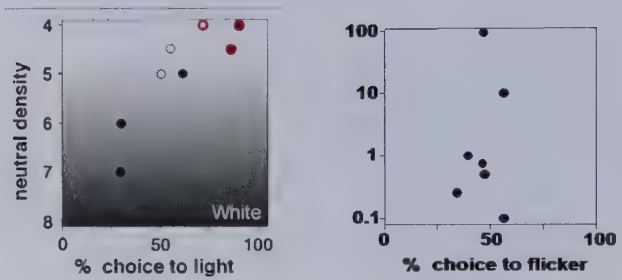


Figure 6.--Light brightness and turtles' behavioral responses.

Fritsches presented plans to conduct work on leatherback (*Dermochelys coriacea*) visual anatomy and physiology. She proposed to examine the gross anatomy of the eye; in particular, the heavily pliated eyelid to examine its role in mucus/salt secretion. Given the leatherback's nearly exclusive diet of jellyfish, she speculated on the eyes serving a large role in osmoregulation. Fritsches plans to section eyes for optical acuity and sensitivity studies. Additionally, Fritsches will investigate receptor anatomy to measure receptor densities, dimensions, types, and presence of oil droplets involved in color vision.

Fritsches is interested in determining if leatherbacks can "accommodate" their lenses by changing the shape of the lens, similar to what birds can do under varying light conditions. She is also interested in comparing photoreceptors between green and leatherback turtles. With regard to potential ontogenetic changes in leatherback eyes, she does not believe that there would be dramatic differences between the eyes of adult vs. hatchling leatherbacks other than the differences caused by the increase in eye size from hatchling to adult (increasing acuity and sensitivity to dim light). However, she commented on the great changes in the ecology and feeding behaviour of turtles over their lifetime and the requirements for adaptable vision.

VISUAL PHYSIOLOGY AND ORIENTATION OF JUVENILE LEATHERBACKS AND LOGGERHEADS

Michael Salmon and Jeanette Wyneken
Florida Atlantic University
777 Glades Road
Boca Raton, Florida 33431

Salmon and Wyneken conducted experiments on (1) flicker fusion frequency, (2) spectral (color) sensitivity, and (3) responses to lightsticks and electrolumes in hatchling leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) turtles. Turtles ($n = 6$ per species) used in studies 1 and 2 were those animals that remained in the nest after the other hatchlings had emerged ("stragglers"). Experiment 3 was conducted using post hatchlings being raised in the lab at Florida Atlantic University prior to trials.

Salmon and Wyneken determined flicker fusion frequencies to analyze the speed of vision in hatchling leatherback and loggerhead turtles. The CFF (critical flicker fusion frequency—the fastest flicker rate that the eye is capable of following regardless of intensity) was determined for both turtle species. Preliminary results indicate that leatherback eyes are relatively slow as compared to loggerhead eyes. Leatherback eyes successfully tracked individual pulses of light between 5 and 12 Hz, with a decreased ability to track individual pulses after 12 Hz. Leatherback hatchlings had a recorded CFF between 7 and 12 Hz. Loggerhead eyes were faster, successfully tracking individual light pulses between 5 and 12 Hz, and able to maintain this tracking until 15 Hz, after which point tracking ceased. Loggerhead hatchling eyes had a recorded CFF between 10 and 15 Hz (Fig. 1). Salmon and Wyneken hypothesize the slow speed of leatherback eyes may be a result of their being obligate gelatinovores. Wyneken cautioned against using stragglers for behavioral assays as these turtles could have different physiological capabilities compared to turtles that emerged from the nest.

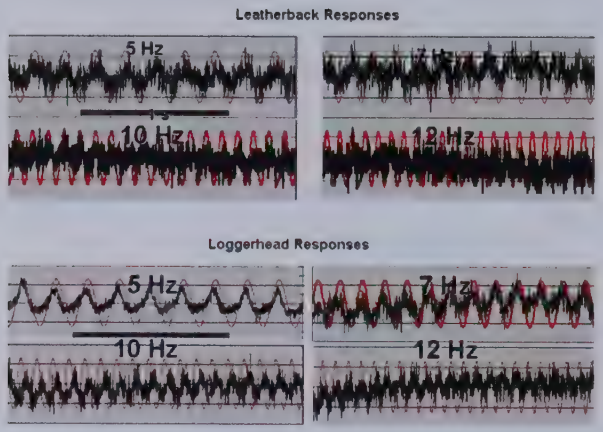


Figure 1.--Tracking capabilities of leatherback and loggerhead retinas to varying speeds of individual light pulses. These electroretinagrams are from retinal cup preparations without the vitreous, lens, and cornea. Oscillating red line shows the flash rate. The light is on at maximum intensity at the top of each cycle, and off at the bottom of each cycle. Retina responses are shown by the black line.

Salmon and Wyneken also examined the spectral sensitivities of both loggerheads and leatherbacks. Their findings indicate that the retinae of both loggerheads and leatherbacks have a very broad sensitivity, with peaks around 360–300 nm and 460–540 nm, allowing them to see from the UV to the red (Fig. 2). Leatherback eyes are less sensitive to the longer (and perhaps to the shorter) wavelengths than loggerheads, suggesting an adaptation to their deep-diving ecology. Blue-green sensitivity may be related to optimal light transmission in continental shelf waters; significance of near UV sensitivity is unknown (potential role in the detection of prey and/or predators?). Wyneken noted our limited knowledge of turtles' use of UV light at present.

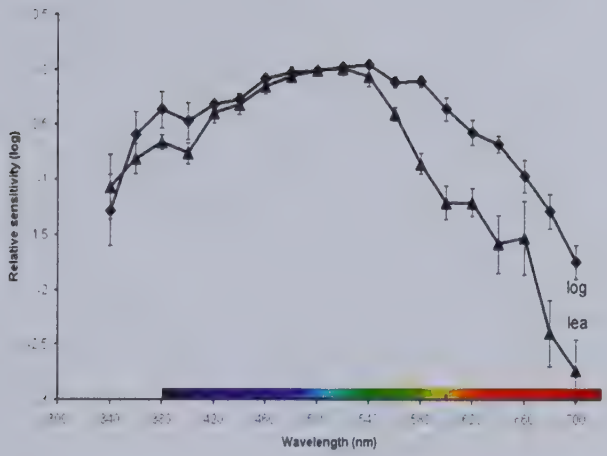


Figure 2.--Spectral sensitivities of leatherback (lea) and loggerhead (log) hatchling turtles.

Salmon and Wyneken also examined the behavioral responses of captive-reared leatherbacks (n = 16) to lightsticks and electralumes. The turtles' orientation behaviors in the presence of lightsticks and electralumes were compared to behaviors in control settings (inactivated lightsticks and electralumes). All studies were conducted at night while turtles were tethered to a lever arm so as to record orientation. Results indicate that juvenile leatherbacks were not behaviorally attracted to the lights, showing no specific orientation to any activated lights (Fig. 3). One potential caveat with this study may be that juvenile leatherbacks are relatively inactive at night—similar to juvenile loggerheads; some turtles did not appear to fully awaken from sleep. Another potentially confounded variable is that the size class of loggerheads studied is known to be entirely diurnal. It is unknown whether leatherbacks are diurnal at this age. The authors could not rule out that possibility. Wyneken suggested that further experiments could be conducted during the day, using fasted turtles in the presence and absence of food odors as a stimulus. Potential ontogenetic changes in responses to lights were discussed.

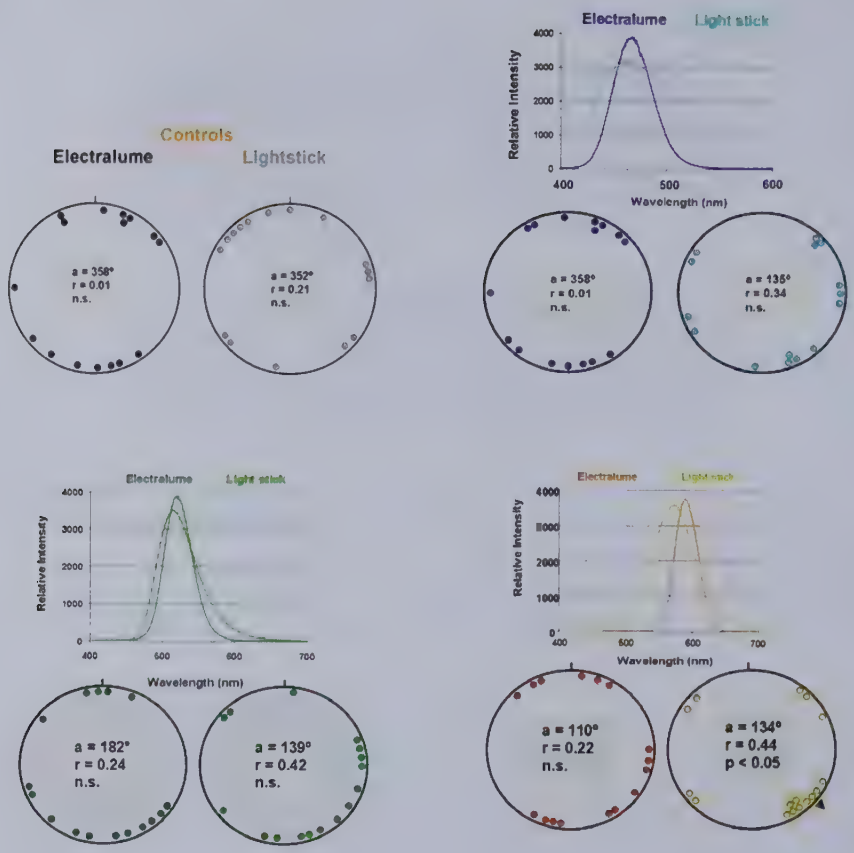


Figure 3.--Orientation of captive-reared leatherbacks to lightsticks and electralumes under three experiments (light spectra) and control conditions (no light). In each diagram, upper graph shows spectrum of light transmitted by the light source (except in the top left pair of the diagram's figure, where there was no light because this was a control). The circle diagrams show orientation; each point is a turtle's heading. The 12 o'clock mark is the position of the light (off, in this case).

SPECTRAL AND TEMPORAL SENSITIVITY OF ADULT AND HATCHLING LEATHERBACK SEA TURTLES

Michael A. Crognale
Department of Psychology
University of Nevada
Reno, Nevada 89557

Scott Eckert
WIDECAST
Duke University Marine Laboratory
Beaufort, North Carolina 28516-9721

Michaele Crognale and Scott Eckert examined the spectral and temporal sensitivities of nesting leatherback (*Dermochelys coriacea*)females on the beaches of Trinidad in the southern Caribbean. They also compared spectral and temporal data between adult and hatchling leatherback turtles.

Results from one field season indicate that nesting (female) leatherbacks ($n = 5$) have spectral (color) sensitivities that appear to be rod-dominated. Alternatively, they could possess "rod-like" cones. With very bright lights and slow flicker, leatherback, green, and loggerhead turtles have similar long wavelength cone pigments but different short wavelength sensitivity (Fig. 1). Under natural conditions, leatherback sensitivity will be shifted to shorter wavelengths with no short-wavelength cutoff filter.

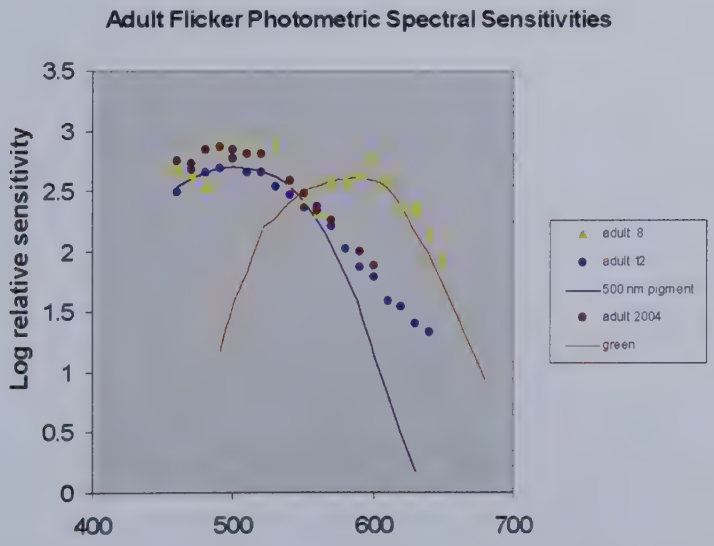


Figure 1.--Spectral sensitivities of adult leatherback turtles (3) and a green turtle (1).

Two techniques were used to measure spectral sensitivity:

1. *Flicker photometric flicker photometric ERGs*—used to compare the amplitude and phase of responses from different wavelengths of flickering test light of adjustable intensity with the responses from a flickering broad band white light of fixed intensity. The intensity of the test light, where the responses are equivalent to those of the fixed light, is taken as a criterion response. This technique removes variability from fluctuations in stimulus conditions and general sensitivity but can be problematic if the cone systems have differing temporal properties.

2. *Criterion threshold technique*—measures the response to flickering light for a logarithmically increasing series of intensities.

Leatherback hatchlings (n = 14) and adults (n = 5) were found to have similar pigment complements. Under natural conditions, however, the adults will have relatively reduced long wavelength sensitivity. Functional short wavelength or UV cone pigments may be present. Difficulties involved in these tests were discussed largely because of changes in actual light levels perceived by the retina, based on differences in the size of the pupils between adult and hatchling turtles. With regards to cornea sensitivity, only leatherbacks appear able to see in wavelengths between 400–500 nm. In hatchlings, this peak is at 440 nm, which is likely the result of more than 1 pigment (Fig. 2).

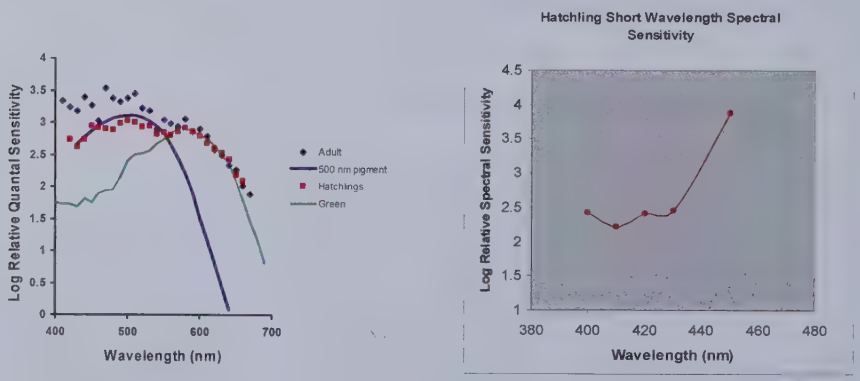


Figure 2.--Spectral sensitivities among hatchling and adult leatherback turtles.

Leatherbacks have relatively poor temporal resolution, which is a measure of the animal's ability to perceive individual light pulses or its speed of vision. Leatherback adult and hatchling middle and long wave cone responses have low-pass temporal sensitivities (rod-like). Of significant note in the findings is the rapid falloff in flicker sensitivity for the leatherbacks and the low-pass nature of the function. Note also that these data are true tuning functions generated from intensity response series like the spectral data and not just amplitude vs. flicker curves. The strong dependence of flicker sensitivity on light levels necessitates this rather more lengthy procedure (Fig. 3).

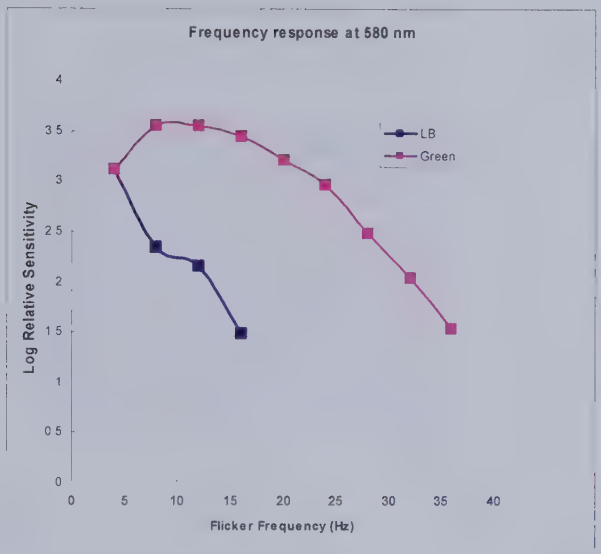


Figure 3.--Temporal resolution between leatherback (LB) and green (Green) turtles.

Leatherback adults and hatchlings were found to have different temporal responses, which could be based on different light levels that reach the retina (based on differences in eye size). Under natural conditions, adult leatherbacks will have lower temporal resolution than will hatchlings. Nonetheless, adult and hatchling temporal responses at all wavelengths are relatively slow.

The figure below (Fig. 4) shows the data collected from five adult and seven hatchling leatherback turtles at two different wavelengths, displaying their low-pass nature and the rapid loss in sensitivity with flicker rate. Note that the hatchling temporal responses fall off slower than those of the adults but are relatively slow for many animals. Note also that the relative sensitivity losses between 500 and 580 nm are very similar. The adult curve looks very rod like. However, the spectral sensitivity of these two wavelengths argues against that (540–562 nm) and certainly the 580 nm curves are not from rods. The difference in temporal response between the adults and the hatchlings could be explained by a difference in light levels just as differences in spectral sensitivity could be explained by light levels. (Fig. 4).

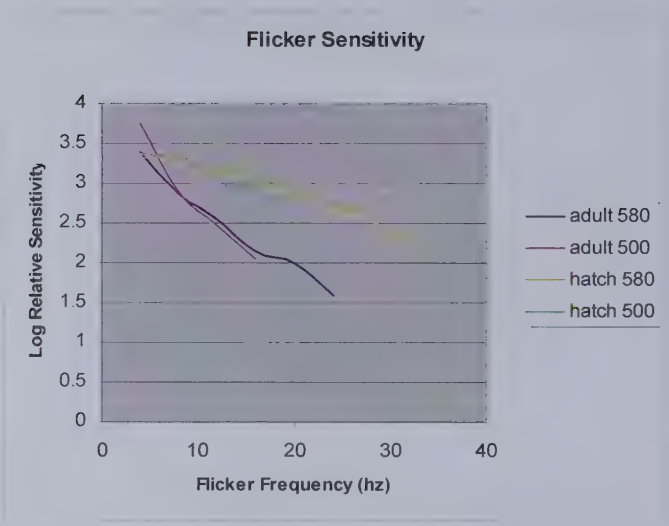


Figure 4.--Flicker sensitivities of hatchling and adult leatherback turtles.

USING PAIRS OF LEDS TO CREATE METAMERS OF UNDERWATER LIGHT IN TURTLE COLOR SPACE

Sönke Johnsen
Biology Department
Duke University
Durham, North Carolina 27708
sjohnsen@duke.edu

Using different colored Light Emitting Diodes (LEDs) at varying levels of brightness and flashing at different rates, Johnsen proposed to create an optical appearance whereby modified LEDs would match the background color of the ocean and thus become invisible for sea turtles and remain visible for fish. Programmed correctly, the combination of LED brightness and flash rates could essentially blend to form a "metamer" to match the color of coastal water or of deep-sea oceanic water. (A metamer has different spectral distributions that are perceived as identical colors.) Given physiological differences in temporal resolution between pelagic fish and sea turtles (previously identified from participants in this working group), Johnsen proposes to exploit these differences and to program an LED to flash such that fish with a higher resolving power could see a flashing light and turtles with slower resolution would see a solid color. Furthermore, by mixing the colors, the light could blend in with the background and thus become virtually invisible to a sea turtle.

Using data on estimated receptor curves for sea turtles, LEDs can be programmed so that turtles will perceive them as matching the background (i.e., should not see the light) while swordfish will see two different flashing lights (Fig. 1). Some species of squid (e.g., Hawaiian bobtail) use a "flashlight" similar to this as a way of imitating the moonlight so that they do not cast a visible shadow, thereby reducing their detection and vulnerability to predatory fish from below.

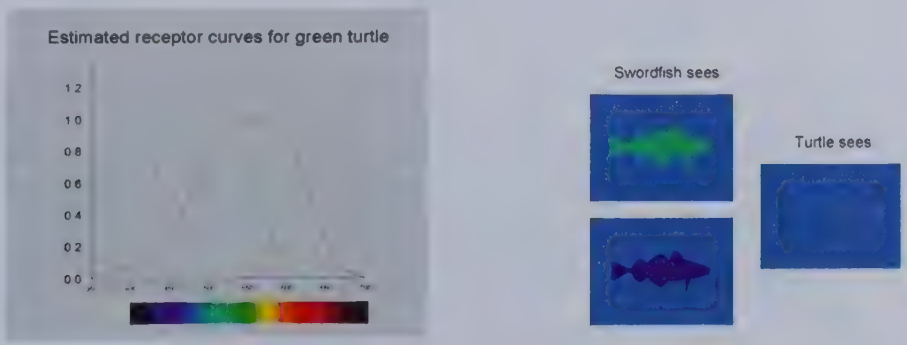


Figure 1.--Estimated receptor curves for green turtles and the perceived colors of modified LEDs as viewed by swordfish and turtles.

Depending on background (ocean) color one wants to match, one can mix and match flashing LEDs with varying frequencies and flash rates. The limitation to this strategy is that one must know the background light conditions (Fig. 2) prior to designing the LED variables. Furthermore, one must also have an excellent understanding of the receptor curves for the animals interacting with the gear.

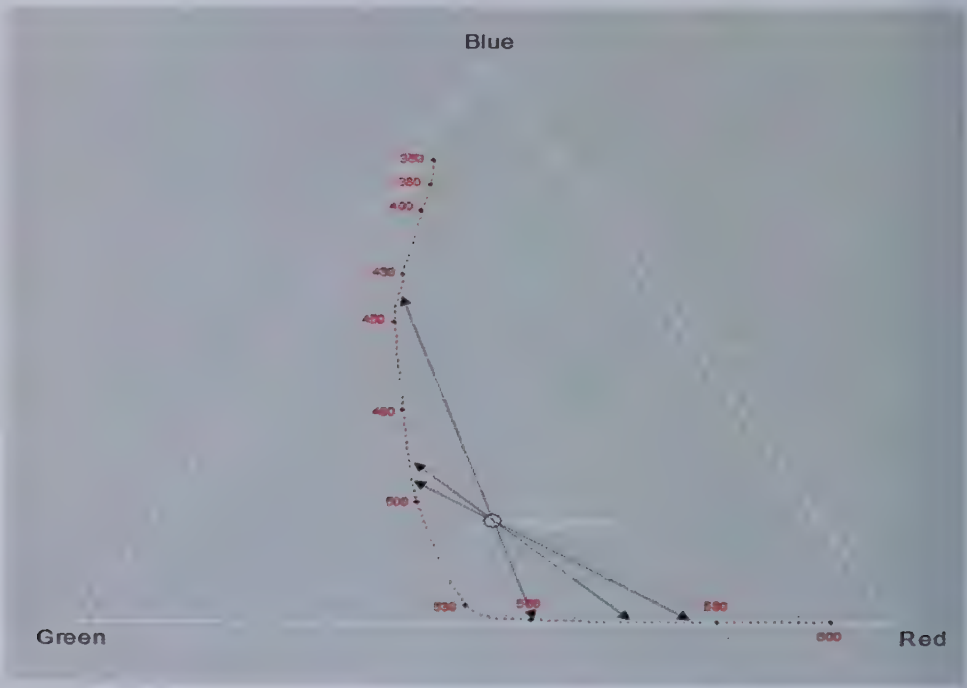


Figure 2.--LEDs can be modified to match background ocean color. Different wavelength distributions which have the same chromaticity and color response are called *metamers*. For example, a yellow formed by monochromatic light at 580 nm looks the same as a roughly equal mixture of 560 nm and 610 nm light; these are metamers of each other. Different chromaticities that lie across gray from each other are called *complementaries*. Additions of any two chromaticities lie on the line between them; additions of any three chromaticities lie in the triangle between them.

BEHAVIORAL RESPONSES OF SEA TURTLES TO PROTOTYPE EXPERIMENTAL LIGHTSTICKS

Kenneth J. Lohmann
Department of Biology
University of North Carolina
Chapel Hill, North Carolina 27599-3175
klohmann@email.unc.edu

John H. Wang
Joint Institute for Marine and Atmospheric Research
University of Hawaii
2570 Dole Street
Honolulu, Hawaii 96822-2396

Lohmann and Wang conducted behavioral experiments using lightsticks in an effort to identify a means to attract fish but not sea turtles, thereby reducing turtles' incidental capture in longline fishing gear. The research conducted in these experiments was built on previously identified methodology aimed to assess the influence of vision in turtles' attraction to fishing gear, specifically lightsticks. Working with juvenile loggerhead turtles (*Caretta caretta*), previous studies found that all activated lightsticks attracted turtles (Fig. 1).

Figure 1.--Lightsticks tested in behavioral experiments. Essentially all colors and types of activated light attracted turtles to orient towards the light source (0^{o}).

Four approaches to making lightsticks less attractive to sea turtles were examined:

1. Lohmann and Wang added circuitry to battery-powered LEDs to make the LEDs blink at specific rates. This allowed them to determine whether blinking lightsticks are less attractive to turtles. Results from these experiments showed that turtles were not attracted to LEDs on less than 42% of a 2.4-s cycle (Fig. 2).

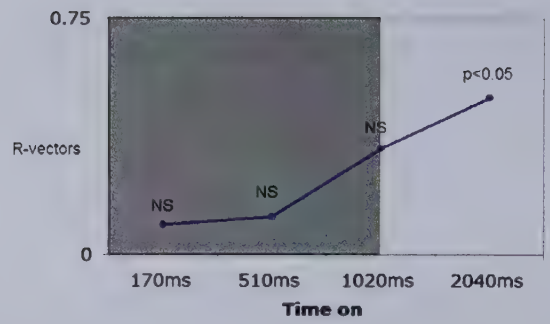


Figure 2.--Loggerhead turtles were not attracted to LEDs until flashing commenced at 42% of 2.4-s cycle.

2. Lohmann and Wang shaded lightsticks so that light would shine downwards, thereby showing lights less visible to turtles that swim predominantly in depths less than 40 m. Behavioral experiments conducted with juvenile loggerhead turtles in Galveston, Texas, with shaded lightsticks in tanks only 3 m deep suggested less swimming behavior in the presence of shaded lights (Fig. 3).

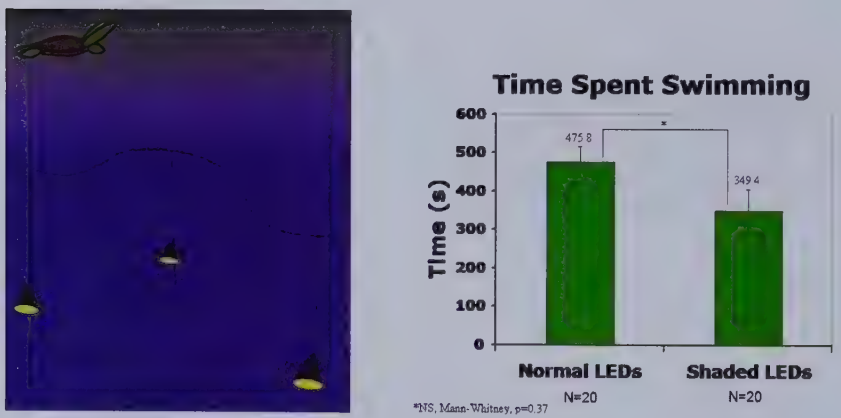


Figure 3.--Directing lights downward presumably makes the lights more difficult to perceive from above. Trials with captive loggerhead turtles suggested that, even in shallow tanks, turtles tended to swim less in the presence of shaded lightsticks than they do in the presence of normal lightsticks. These differences may be magnified under conditions in which the lights are much farther from the surface, as occurs in the ocean (control (normal) $N = 20$, experimental (shaded) $N = 20$).

3. Hatchling loggerheads on the beach have been reported to avoid a narrow band of wavelengths in the 560–600 nm range. Previous work has demonstrated that lightsticks producing these wavelengths fail to repel turtles if the lightsticks also produce some other wavelengths. An experimental lightstick was, therefore, developed that produces only a narrow band of wavelengths that approximately matches the 560–600 nm range. Tests with this lightstick (570 nm peak) suggested that turtles are less attracted to this lightstick than to the LEDs (Fig. 4), although some turtles still swam in the approximate direction of the light.

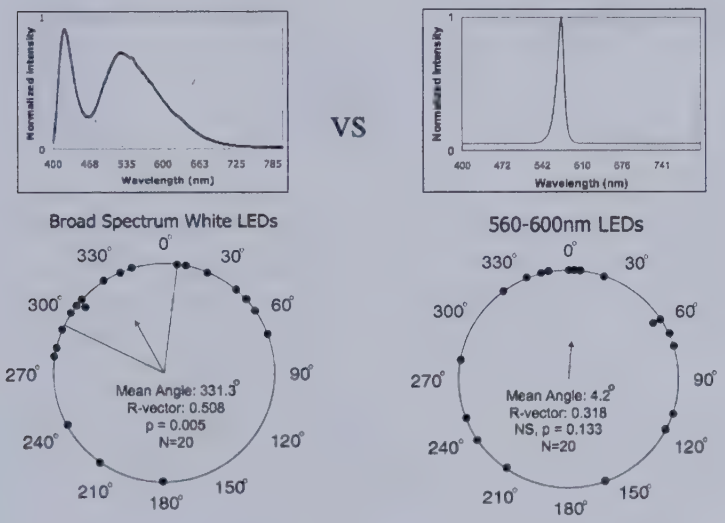


Figure 4.--Juvenile loggerhead turtles were attracted to all activated lights, but appear to be less attracted to LEDs that produce light in the 560-600 nm range than they are to other sources of illumination.

4. Lohmann and Wang are collaborating with Sönke Johnsen (see presentation by Sönke Johnsen) to develop lightsticks that are invisible to sea turtles but can be perceived by fish.

PRELIMINARY FIELD EXPERIMENTS IN BAJA CALIFORNIA, MEXICO WITH LIGHTSTICKS AND SHARK SHAPES

John H. Wang
Joint Institute for Marine and Atmospheric Research
University of Hawaii
2570 Dole Street
Honolulu, Hawaii 96822-2396

Yonat Swimmer
Pacific Islands Fisheries Science Center
National Marine Fisheries Service
2570 Dole Street
Honolulu, Hawaii 96822-2396

Wang and Swimmer conducted field experiments in Baja California, Mexico to determine whether lightsticks and shark shapes had an effect on sea turtle catch rates in a coastal gill-net fishery. Work was conducted with a student volunteer organization as well as with local fishermen and Mexican-based turtle conservation organizations (e.g., Grupo Tortuguero). Field work was conducted in both the Sea of Cortez and the Pacific side of the Baja Peninsula.

Preliminary trials suggest that the presence of activated lightsticks may reduce the number of green turtles (*Chelonia mydas*) caught in the nets. Wang and Swimmer hypothesize that such a phenomenon is likely a result of the increased visibility of the nets from lightstick illumination. This finding suggests the promising use of lightsticks in both net and longline fisheries to reduce turtle interactions (Fig. 1). More field trials are needed to increase sample size to test this with sufficient statistical power. Work is planned for summer 2007.

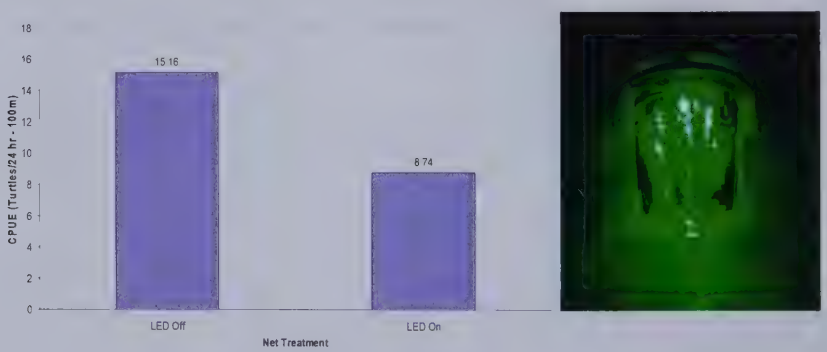


Figure 1.--Capture rate of turtles in nets with activated lightsticks (LEDOn) vs. inactivated lightsticks (LEDOff).

Preliminary trials also suggest that the presence of shark shapes on nets decreases the number of turtles caught (Fig. 2). More field trials are needed to increase sample size to test this with adequate statistical power. Work is planned for summer 2007.

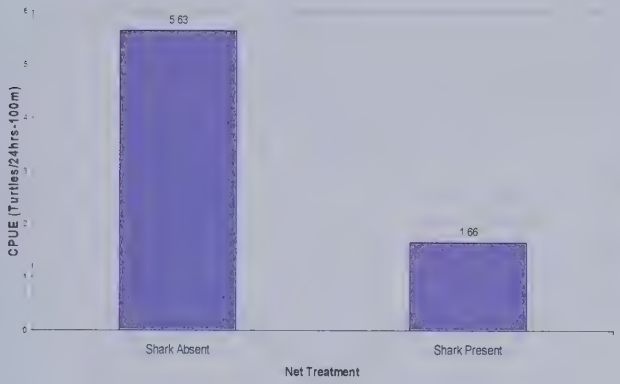
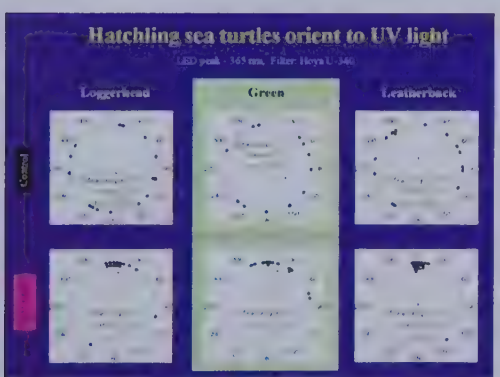


Figure 2.--Capture rate of turtles in nets with (SharkPresent) and without (SharkAbsent) shark shapes. Silhouette of shark shape attached to nets.

Preliminary behavioral experiments show that turtles can see UV light. Physiological experiments show that billfish and mahimahi cannot see in the UV range. Clear UV-absorbing plastics will therefore be transparent to some pelagic fish, but will appear as black silhouettes to sea turtles (Fig. 3). Shark-shaped banners can potentially be made of clear UV-absorbing plastics that could warn turtles to stay clear of fishing gear, thereby reducing turtle-fisheries interactions.



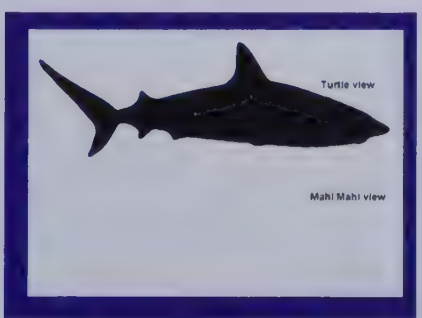


Figure 3.--At left, data indicating hatchling turtles' orientation (and detection) of UV light from previous work (Wang and Lohmann, unpublished data). At right, how a shark shape made of UV-absorbing plastic would appear to a turtle (top) versus a mahimahi (bottom).

UPDATES ON THE USE OF MAGNETS AND E+ METALS AS SHARK REPELLENTS

Eric Stroud
Shark Defenses, Inc.
P.O. Box 2593
Oak Ridge, New Jersey 07438

A variety of methods have been examined to reduce interactions between sharks and longline fishing gear. These methods can be classified under three broad categories: (1) chemical repellents, (2) magnetic repellents, and (3) electropositive metal repellents.

Potential chemical repellants include semiochemical extractions (SharkDefense A2, extracted from decayed shark tissue) or a time-release gel (SharkDefense G2, a combination of 3-methylbutanal, *(E)*-2 butenoic acid, and a gel matrix). Experiments examining the necessary dose size (chemical cloud) to terminate tonic immobility in sharks were conducted (Figs. 1, 2, and 3).

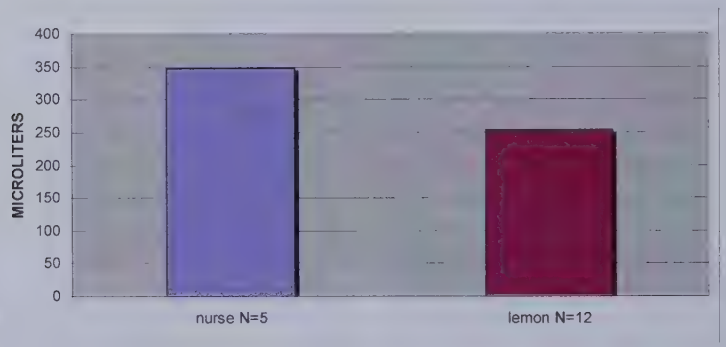


Figure 1.--Average volume of 3-methylbutanal in microliters required to terminate tonic immobility in juvenile nurse sharks and juvenile lemon sharks using a directed oral dosage. Repellency was observed in the range of 250 uL to 350 uL.

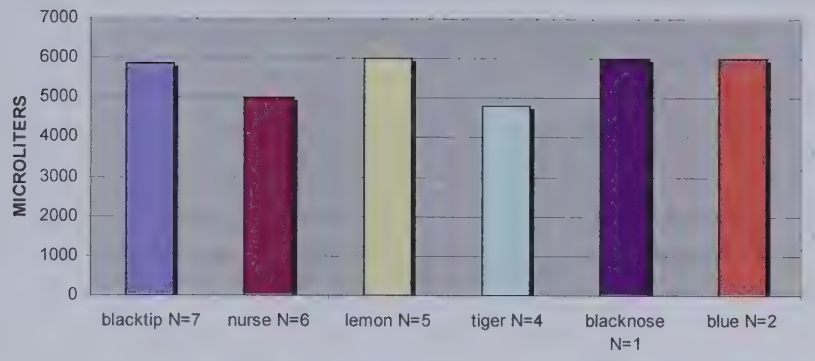


Figure 2.--Average volume of 3-methylbutanal in microliters required to terminate tonic immobility in various shark species using a dose released at least 15 cm from the nares.

Figure 3.--Average volume of *(E)*-2 butenoic acid in microliters required to terminate tonic immobility in various shark species using a dose released at least 15 cm from the nares.

Studies with captive yellowfin tuna (*Thunnus albacares*) and cobia (*Rachycentron canadum*), as well as observations of six species of reef teleosts during repellent tests show that the fish are not aversive to the active compounds in SharkDefense A2 and G2, making these compounds selective to sharks. In one 2006 longline study, an adult horse-eye jack (*Caranx latus*) represented the only catch on a repellent treatment line. Crabs are also routinely observed on repellent treatments.

SharkDefense G2 has been formulated into a time-release gel that lasts 6 hours in seawater. This gel is based on a glycol ether and a hydroxy-propylmethylcellulose thickener. Preliminary data from initial field trials using demersal longlines in the Bahamas indicate that

no sharks were captured on hooks with the time release gel. Based on a small sample size and low shark catch-per-unit-of-effort (CPUE), more studies are required to achieve results with satisfactory statistical confidence.

Powerful Neodymium-iron-boride permanent magnets were shown to terminate tonic immobility in juvenile sharks. Magnet fluxes of 50 Gauss or greater terminated tonic immobility in juvenile sharks; however, there was a diminishing response with continuing exposure. Preliminary data from demersal longline trials in the Bahamas indicate that no sharks were captured on hooks with magnetic treatments. Once again, field trials did not catch enough sharks to determine the effects of magnets on shark CPUE with sufficient statistical confidence.

A recent discovery by SharkDefense shows that electropositive metals (e.g., Neodymium, Praseodymium, early Lanthanide metals, Mischmetal, and Magnesium) also terminate tonic immobility in juvenile sharks. These metals, which are also present in rare earth magnets, may be responsible for some of the repellency effect seen with permanent magnets and present a more practical alternative (Figs. 4 and 5).

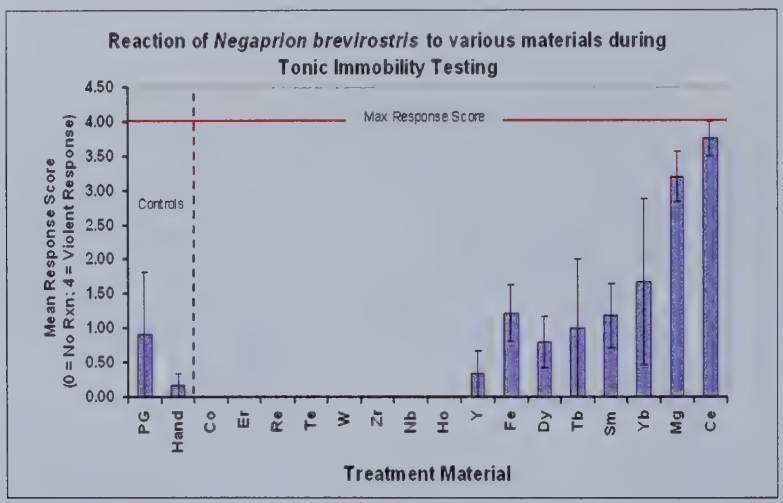


Figure 4.--Overall reaction of immobilized juvenile lemon sharks, *Negaprion brevirostris*, when exposed to various test materials during tonic immobility.
PG = pyrolytic graphite; Hand = bare hand; Co = cobalt; Er = Erbium; Re = Rhenium; Te = Tellurium; W = Tungsten; Zr = Zirconium; Nb (sic) = Niobium; Ho = Holmium; Y = Yttrium; Fe = Iron; Dy = Dysprosium; Tb = Terbium; Sm = Samarium; Yb = Ytterbium; Mg = Magnesium; Ce = Cerium.

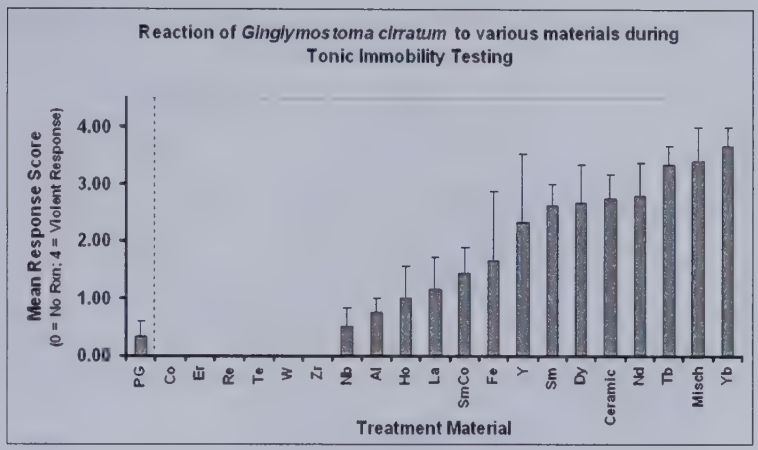


Figure 5.--Reaction of immobilized juvenile nurse sharks, *Ginglymostoma cirratum*, when exposed to various test materials (chemical element symbols) during tonic immobility. PG = pyrolytic graphite; Co = cobalt; Er = erbium; Re = rhenium; Te = tellurium; W = tungsten; Zr = zirconium; Nb (sic) = niobium; Al = aluminum; Ho = holmium; La = lanthanum; SmCo = samarium cobalt; Fe = iron; Y = yttrium; Sm = samarium; Dy = dysprosium, Ceramic = barium-ferrite ceramic magnet; Nd = neodymium; Tb = terbium; Misch = cerium misch metal (lanthanide alloy), Yb = ytterbium.

These metals are not inherently magnetic (they are not ferromagnetic). A correlation has been found between the standard oxidation potential of these metals and the behavioral response of immobilized sharks. At present, only tonic immobility trials and magnetic fence experiments in closed pens in the Bahamas have been conducted with favorable results. An initial longline study is planned.

With respect to sea turtles, repellency tests on sea turtles are proposed as a means to develop a bycatch reduction technology. One series of experiments will determine if sea turtles are chemically aware of their injured or dead (a schreckreaktion) counterparts. This experiment will involve controlled presentations of fresh and decayed turtle tissue with behavioral observations. A second series of experiments will determine if sea turtles respond to strong permanent magnetic fields. As sea turtles are magnetite-based magnetoreceptive animals, a series of experiments will attempt to produce aversive behavior in the presence of permanent magnets. A third series of experiments will determine if sea turtles can detect electrical currents created by electropositive metals in seawater. These metals act as galvanic cells in seawater, producing voltages of up to 1.6eV. Behavioral observations will be made in the presence of a series of pure electropositive metals, including the Lanthanides, mischmetal, and magnesium.

FUNCTIONAL ANALYSIS OF BITING IN LOGGERHEAD TURTLES (*CARETTA CARETTA*)

Christopher Marshall
Texas A&M University
College Station, Texas 77843

Loggerhead turtles (*Caretta caretta*) are renowned for their biting ability. Marshall examined whether the natural ability of loggerhead turtles to excel in biting results in greater hooking and how the biomechanics of biting could be used to identify means of reducing the likelihood of turtles' biting fishing gear. To study this, Marshall measured the ontogeny of in-vivo bite force in loggerheads (Fig. 1).

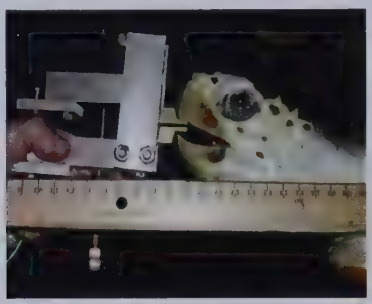


Figure 1.--Use of a transducer to measure bite force in a captive loggerhead turtle.

The bite force of these animals was positively correlated with carapace length and mass of the turtle (Fig. 2).

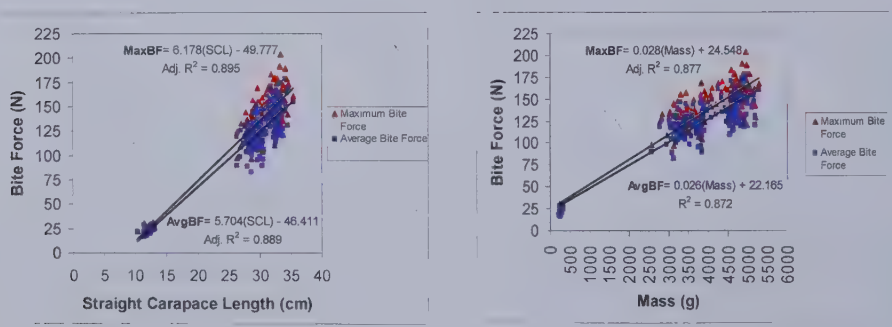


Figure 2.--Correlation of bite force with straight carapace length and mass of the turtle.

Marshall also quantified the feeding behavior of hook biting using motion analysis (Fig. 3). Depending on bait, he noted a certain amount of 'sucking' behavior that could lead to deeper hooking events.

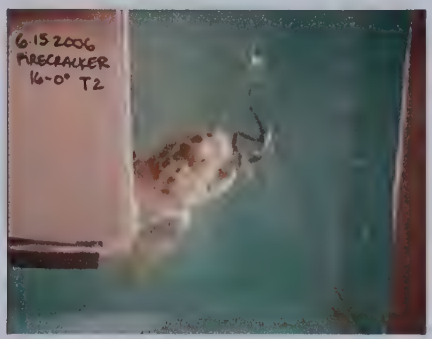


Figure 3.--The biomechanics of biting was quantified using motion analysis in captive loggerhead turtles.

Marshall plans to characterize the jaw-joint biomechanics and morphology using Finite Element Analysis. This methodology potentially allows the examination of stress/strain points on the jaw and skull of the animal.

LEATHERBACKS IN CAPTIVITY: GROWTH AND HEALTH

T. Todd Jones
University of British Columbia
2329 West Mall Vancouver
BC Canada V6T 1Z4

Since 1936, several researchers have attempted to raise leatherbacks (*Dermochelys coriacea*) in captivity, with limited success. Only three animals were ever maintained for more than 1 year post hatching. All reports indicate exhaustive efforts are required to maintain leatherbacks alive for any length of time (especially in comparison to other species of marine turtle).

During the past 3 years, 27 leatherback hatchlings born on beaches in the British Virgin Islands have been reared at the University of British Columbia (UBC). Three main issues were examined in the process of rearing turtles for various physiological experiments.

1. Leatherbacks do not recognize physical barriers, most likely as a result of their oceanic-pelagic lifestyle. This required constant use of tethers to prevent the animals from constantly hitting the tank's bottom and side walls (Fig. 1).

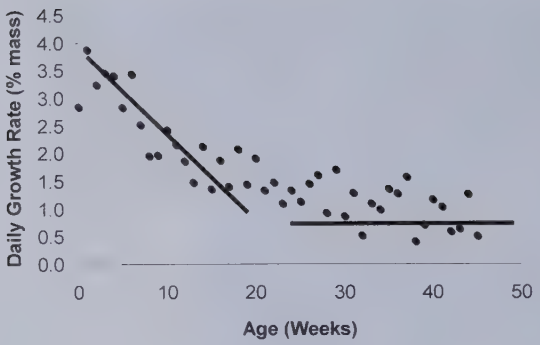
Figure 1.--Leatherback hatchlings in tanks at the UBC.

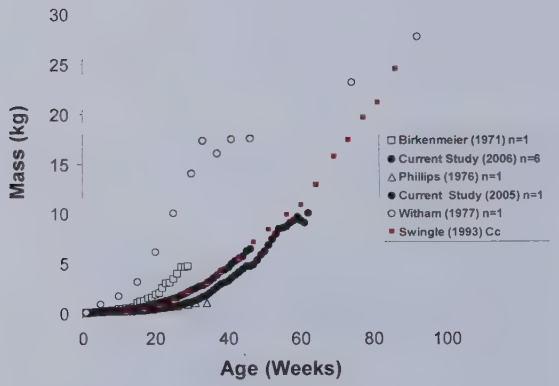
2. As leatherbacks are gelativores (feed solely on gelatinous zooplankton) their health and proper growth in captivity required a specialized diet—a squid jello diet was formulated, made daily, and strips were hand fed to the turtles (Fig. 2).

Figure 2.--To ensure growth, squid jello strips were fed daily to turtles.

3. Leatherbacks are highly susceptible to bacterial and fungal infections. To prevent infections, particular attention was paid to water quality. An overview of health issues includes rostral abrasions, pink spot ulcerative dermatitis, hemorrhagic foci, and bacterial pneumonia.

Growth rates of the captive leatherbacks showed an initial burst in growth. Characteristics of this growth include an initial burst of 4% of body mass gain per day (28% per week). This initial growth later slowed to ~ 2 % of body mass gain per day (15% per week) at 15 weeks of age. By 20 weeks of age, leatherbacks gained on average 1% of body mass per day. Based on these growth trajectories, it is hypothesized that leatherbacks in captivity take $5^{1}/2 - 6$ years to reach a mass equivalent to females found on nesting beaches (Fig. 3).





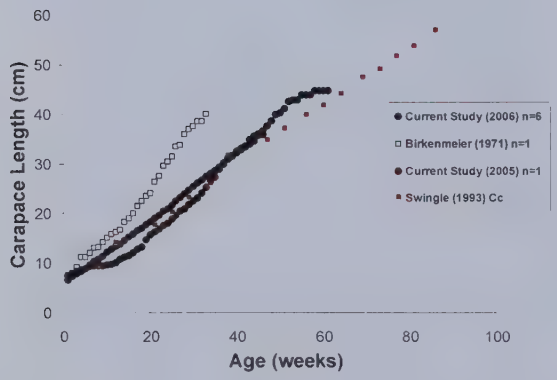


Figure 3.--Growth rates of leatherback turtles in captivity.

COMMENTS ON FUTURE DIRECTIONS

In December 2006, Yonat posed questions to the group of participants of the Sea Turtle and Pelagic Fish Sensory Workshop plus a few additional scientists and asked them to comment on the following:

1. What idea(s) do you believe are most promising in leading to a sea turtle deterrent?

2. What idea(s) show the least promise of leading to a tractable solution?

Below are summarized responses from individuals posted to the group via e-mail (as of January 2007):

Michael Salmon, Florida Atlantic University

(1) Until any of the ideas we've been developing are field-tested on longlines, using an appropriate (single-factor) design, we can't be sure which of them will work and which will not. With that in mind, I think we need to be cautious about concluding anything won't work, at least on the basis of the science. (We might come to that conclusion based on other considerations, such as cost or practicality [for use on board a fishing boat]. But that's another matter entirely...)

(2) We've barely scratched the surface in our investigations of sensory biology and behavior. Furthermore, we unfortunately are working with animals whose basic sensory biology and behavior is largely unknown to begin with, making our task all the more difficult. It's going to take time to overcome that problem, and lots more support. Hopefully, the patience and determination are there to make that possible.

(3) Of the ideas so far developed, I think three should be field-tested ASAP. These are:
(i) Use of flashing lights of different color (Sönke Johnson),
(ii) Shielded/shaded lights (John Wang), and
(iii) Use of shark models (Ben Higgins).

(4) I think an area with great potential is to test baits that have a repulsive taste (to turtles), because predatory fish (unlike turtles) strike first and taste later—and so might be hooked before they are chemically repelled. The efforts in that direction have thus far been unsuccessful, largely because experts in the area (such as Dan Rittschof) were never consulted in the selection of the repellents. I continue to believe that's the wrong approach.

Kenneth J. Lohmann, University of North Carolina, Chapel Hill, North Carolina

It may be helpful to start by just listing possible turtle deterrents and possible ways of decreasing turtle interest in longlines. Below is a starter list of possibilities (in no particular order) that people can add to. I have not made any attempt to assess feasibility or likelihood of success; these are just ideas that emerged at our most recent meeting, and I'm sure that I have overlooked some.

(1) Sönke's selectively invisible lightsticks;
(2) Shading lightsticks so they are less visible to turtles from above but visible to fish below;
(3) Blinking lightsticks that attract fish but not turtles;
(4) Use biomechanical research to develop hooks that are less likely to catch turtles;
(5) Use UV-absorbent shark silhouettes that turtles perceive but fish cannot;
(6) Use some other kind of shark model (the Ben Higgins design) to deter turtles;
(7) Eric Stroud's misch metal (if we get very lucky and it deters turtles but not tuna/swordfish).

I share Rich Brill's view that the best of all possible solutions would be to come up with a turtle-safe bait that attracts fish but does not attract turtles. Unfortunately, the initial olfaction work did not turn up anything that turtles don't like. However, it might be too soon to give up on the idea, given the complexity of the issue and the numerous options that potentially exist.

Finally, in the "not promising" category, we would probably all agree that sound does not appear to be a promising deterrent.

Sönke Johnsen, Duke University, North Carolina

I pretty much echo Ken's comments. A chemical deterrent is still the best, but we just don't seem to have one. I think visual deterrents and visual camouflage are still great possibilities. The shark stuff really appeals to me, since it would be simple to do. I worry that the turtles will acclimate to them though. The misch metal is very cool, but I don't know if it will do the right thing for the animals we care about.

Jeanette Wyneken, Florida Atlantic University, Florida

First, the premise that the group started with, that understanding the fundamentals of the species' behavior (broadly defined to include physiology) is critical, still stands as a solid foundation. Not surprisingly, with so little known about sea turtle sensory systems and how they compared to the target fish species, we all had to build the foundations first before applications could be reasonably explored. So, for summary purposes it is probably safe to break down the achievements of the group into three categories.

The process of preventing or deterring turtles (these are not necessarily the same thing) from interacting with longlines has three levels:

(1) Identification of key aspects of the several sensory systems' characteristics (what signals are possible for the animals to detect? What is possible?).
(2) Identifying which aspects of the gear, bait, and surrounding environment are physiologically or theoretically detected and which are actually used (Allowing the behavior to tell us what the animals use).
(3) Application of that new knowledge in testing methods or gear deterrents and prevention of turtle biting the hooks or becoming foul-hooked.

In reality, we are just now getting to the point where the level of understanding is robust enough to design deterrents or preventers. So, in many ways, it is premature to do a lot of ranking since we are still dealing with parts i and ii while bringing part iii on line. That we even have potential solutions after the 3–5 years is quite fast given the starting points.

As Ken suggests, multiple approaches will allow us (and those who use our work) to build alternative solutions. I don't think I am naive in suggesting that solutions may end up being fleet-specific or region-specific given the diversity in the various longline fisheries. It seems that providing a diverse set of possible solutions, whether they are camouflaged lights, chemicals, electromagnetic disrupters, hook guards and other hook modifications, new forms of lines, shifts in set timing, etc., will provide a "toolkit" for the fishers and gear specialists to draw from. Continuing to explore and develop methods to deter turtles from approaching the baits/lines or to prevent their capture (should they not be deterred), will require multiple approaches and some additional or continued study of turtle behavior. Thus, we should not abandon steps i and ii while testing solutions. Providing a set of options that includes continued dialogue with and within this highly collegial group will be a strong statement. The group is a resource that can continue to provide perspective and expertise.

I echo much of what Ken brought forward. I add a couple of areas that should remain high priorities.

(1) Developing better understanding of the similarities and differences in leatherback vs. loggerhead behavior around the lines. We seem to be missing a robust understanding of what constitutes normal behavior for each species with and without lines present. That information is a step back from the fine scale understanding of the sensory systems. Do the turtles come swimming in when lines are deployed? It seems critical to know how turtle movements change when the lines, baits and hooks go in the water.

(2) I agree with Sönke and Ken that chemical cues need some reexamination. Sea turtles and fish are still vertebrates and there is a rich history of using chemical cues to alter behavior in a whole suite of species. The studies to date may not direct us in ways we had hoped, but they set some groundwork and suggest avenues to pursue that can tell us what doesn't matter to turtles and hint at what remains to be asked.

(3) I also agree that the shark shapes are appealing because they are simple, they take advantage of materials that one may reasonably find on a fishing boat, they may be applicable to other fisheries, and the concept works in practice for a number of other vertebrates.

Finally, while a great deal of progress has been made, it is likely that not everything will work for *both* species, or in many cases we don't know what works for leatherbacks yet. Thus, I am very cautious about what I would label as less promising. I would limit this list to things that the turtles simply cannot detect, ignore (like sound), or things that turtles easily acclimate to as their deterrent/ prevention values are too short-lived to make a big difference.

Kerstin Fritsches, University of Queensland, Australia

Thanks everyone for very interesting contributions.

I think Jeanette's point is a very important one: it's unlikely that there will be one deterrent that works in all areas and for all species and my feeling is that if there was the one deterrent that works I think we would have found it by now. So I very much like Jeanette's suggestion of a "toolbox" for different situations.

As a survival strategy I would expect a turtle to follow up on any anomaly they can trace to check if there is any food there. So a deterrent might work for a while but I agree with Soenke that they might just get used to it. But then Ben said his captive turtles didn't habituate, so I think the shark shape option is a promising one.

A line and bait in the water will be an inherent attractant, so anything we can do to make it less visible/noticeable to a turtle should reduce interactions and the options that Ken listed will all do this in different ways. I guess the grading of these options will need to take into consideration cost and likelihood of these measures being applied by the fishermen. Then pick the ones that are most likely to work in practice.

Also Jeanette's point about the differences between loggerheads and leatherbacks is a very important one. To me it sounds as if for loggerheads the lines and gear should be as invisible / unnoticeable as possible as they want to actively feed on the bait. On the other hand leatherbacks get tangled swimming into the lines and they appear not to be interested in the bait anyway so it would make sense to make the gear as visible as possible to this species to prevent entanglement. But whether visible lines still catch fish is the other question that needs to be answered. Or maybe we can design lines that are only visible to turtles, using UV for example (not visible to the fish). So measures might need to be very area-specific to work and might have to cater differently for the different species.

So I agree with the others that it might just be too early to exclude strategies, as it might all depend on the situation and the species.

Sheryan Epperly, NOAA-NMFS, Southeast Fisheries Science Center, Miami, Florida

I'll chime in and say that I agree with Jeanette and Kerstin. I'd like to add two things. In the central and western North Atlantic, the concerns are leatherbacks and loggerheads, but elsewhere, interactions with other species (e.g., olive ridley) need to be considered. Thus, our focus should not be solely on leatherbacks and loggerheads. Secondly, I am yet to be convinced that leatherbacks are not attracted to the bait. There could be locomotor reasons that they are entangling before getting the bait in their mouth. In the NED experiments, a greater proportion (of a fewer number) of leatherbacks did ingest circle hooks compared to J hooks. Said differently, the baited circle hooks, which were less likely to foul hook the turtle first, found their way into a greater proportion of leatherbacks' mouths.

Richard Brill, Virginia Institute of Marine Science

I agree with what the other folks have written. I'd just like to add that I think we should try to find some chemo-sensory type(s) to join the group. This avenue probably still holds promise and I'd like to see it being investigated. John Caprio at LSU might be a good candidate.

But more important, we seem to have gotten away from the originally proposed parallel tracks of doing turtle and fish sensory biology work simultaneously. Obviously a procedure that repels turtles likewise has to have no effect on pelagic fishes. However, with the demise of the Kewalo Research Facility as a functional tuna research laboratory, I'm not sure where this work might be done. There is the IATTC facility in Panama, but I've heard rumors that this may be closed due to budget cuts. There are tunas being held in shoreside facilities in Taiwan, but I don't know anything more about this. And, of course, there is always the Tuna Research and Conservation Center at Stanford (Hopkins Marine Station).

Ben Higgins, NOAA-NMFS, Galveston, Texas

Happy New Year! I didn't chime in with a response to the group as I think the others have summarized things pretty well. To summarize the research, it would have been nice, in this order, to have found a:

1. chemical deterrent
2. visual/audio deterrent
3. mechanical deterrent

Based on sensory biology experiments, the most promising are (with varying results lab vs field):

1. mechanical deterrent (modified hooks)
2. visual deterrent (bait color, modified lightsticks, shark shape?)

We [Miami and Pascagoula are PIs, Galveston is hosting research] are testing a smaller hook with a wire appendage right now. It looks promising but we won't know just how promising until we run the turtles at 55 cm in April and at 65 cm in July/Aug. We did 45 cm in Dec 2006.

I hate to give up on the chemical deterrent. I'm pretty sure there is something out there that in high enough concentration, would repel a turtle. It might be species specific though and not necessarily the same across the board for all species. I have 2 captive turtles that will be euthanized this spring. There were 4, but 2 are showing signs of improvement. A sample size of 2 or even 4 really isn't good enough based on how much variability we see working with sea turtles. To really do the chemical work, someone needs to go to the Cayman Turtle Farm and work with animals that are going to be sacrificed and identify at least families of compounds we might try with captive turtles. Plug electrodes right into the brain and pump chemicals through/past their olfactory receptors.

With that said, I plan to keep bringing turtles back after TED testing for sensory biology/longline research until someone tells me not to, and/or there is no money. I am realizing that we [Galveston] just don't have the capability to do both our captive rearing and rehab activities and our own sensory biology research. Hosting research is no problem, and we encourage everyone to make the most use they can out of the captive turtles.

PARTICIPANTS

Richard Brill	Virginia Institute of Marine Science
Mike Crognale	University of Nevada
Wendy Dow	WIDECAST
Scott Eckert	Duke University Beaufort Marine Laboratory
Sheryan Epperly	NOAA Fisheries, Southeast Fisheries Science Center
Kerstin Fritsches	University of Queensland
Ben Higgins	NOAA Fisheries, Galveston Laboratory
Sönke Johnsen	Duke University
T. Todd Jones	University of British Columbia
Peter Lindgren	Lindgren-Pitman, Inc.
Kenneth Lohmann	University of North Carolina
Mark Luckenback	Virginia Institute of Marine Science
Chris Magel	Virginia Institute of Marine Science
Kate Mansfield	Virginia Institute of Marine Science
Christopher Marshall	Texas A & M University
Michael Salmon	Florida Atlantic University
Eric Stroud	Shark Defenses, Inc.
Yonat Swimmer	NOAA Fisheries, Pacific Islands Fisheries Science Center
John Wang	University of Hawaii
Jeanette Wyneken	Florida Atlantic University
Noelle Yochum	Virginia Institute of Marine Science

Front row: Rich Brill, Yonat Swimmer, Kirsten Fritsches, Mike Crognale, Christopher Marshall. Middle row: Chris Magel, John Wang, Wendy Dow, Kate Mansfield, Jeanette Wyneken, Sönke Johnsen, Peter Lindgren, Sheryan Epperly. Back row: Noelle Yochum, Eric Stroud, Ken Lohmann, Ben Higgins, T.Todd Jones, Scott Eckert.

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Y. SWIMMER and R. BRILL
(December 2006)

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S. STEWART and A. GOUGH
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M. PARKE
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